

# A comparative investigation of the efficacy of CO<sub>2</sub> and high-power diode lasers for the forming of EN3 mild steel sheets

J Lawrence

Manufacturing Engineering Division, School of Mechanical and Production Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798

**Abstract:** A comparative investigation of the effectiveness of a high-power diode laser (HPDL) and a CO<sub>2</sub> laser for the forming of thin-section EN3 mild steel sheet has been conducted. The buckling mechanism was identified as the laser forming mechanism responsible for induced bending. For both lasers it was found that the induced bending angles increased with an increasing number of irradiations and high laser powers, while decreasing as the traverse speed was increased. Also, it was apparent from the experimental results that the laser bending angle was only linearly proportional to the number of irradiations when the latter was small due to local material thickening along the bend edge with a high number of irradiations. Owing to the mild steel's greater beam absorption at the HPDL wavelength, larger bending angles were induced when using the HPDL. However, under certain conditions the performance of the CO<sub>2</sub> laser in terms of induced bending angle was seen to approach that of the HPDL. Nevertheless, similar results between the two lasers were only achieved with increasing irradiations; thus it was concluded that the efficacy of the HPDL was higher than that of the CO<sub>2</sub> laser insofar as it was more efficient. From graphical results and the employment of an analytical procedure, the laser line energy range in which accurate control of the HPDL bending of the mild steel sheets could be exercised efficiently was found to be  $53 \text{ J/mm} < P/v < 78 \text{ J/mm}$ , while for the CO<sub>2</sub> laser the range was  $61 \text{ J/mm} < P/v < 85 \text{ J/mm}$ .

**Keywords:** CO<sub>2</sub> laser, high-power diode laser (HPDL), mild steel, sheet, forming, bending, laser materials processing

## 1 INTRODUCTION

There is much to be said for the contemporary industrial laser, for over recent years the notion of the laser as merely another machine tool available to the modern engineer has become a reality. This is certainly true in the case of laser forming, which is increasingly being recognized as a viable alternative to traditional methods in certain applications. What is more, many possibilities exist for the deployment of laser forming within production engineering for alignment and adjustment procedures [1], while complex geometric forms, which ordinarily can only be produced with great difficulty using conventional forming techniques, can be made very easily with laser forming [2]. Despite the fact that the origins of the laser forming technique can be traced back to the established method of flame bending [3, 4],

laser forming is a much more refined and controllable technique that offers numerous unique application possibilities. This extensive variety of possible applications within industry exists due to a number of factors, namely the reasonably high degree of control over the energy transfer, the high levels of accuracy and reproducibility, the very high degrees of flexibility and the non-contact nature of the technique. Such attributes are the direct result of the nature of the operating characteristics of lasers. Consequently, the very fact that the technique is laser-based means that it could be employed to form parts in locations where it would otherwise be impossible to use conventional forming methods, such as in outer space [5].

Laser forming is basically a spring-back-free, non-contact process in which bending is induced by a localized laser-generated temperature gradient between the irradiated surface and the neighbouring material. This temperature distribution forces the material to expand non-uniformly, which in turn leads to non-uniform

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thermal stresses. Where the thermal stresses exceed the yield point of the material, plastic deformation is occasioned. As a consequence, the material initially curves inwards towards the laser beam and then outwards away from it, the latter occurrence being driven by the compressive nature of the thermal stresses induced by the more rigid interior material layers, which are much cooler.

Early work by Namba [5, 6] reported on the potential high degrees of flexibility of the laser-forming process. Since then many researchers have studied various aspects of the technique in great detail. In particular, Vollersten [7, 8], Vollersten and Rödle [9], Vollersten and Holzer [10] and Geiger and Vollersten [11] have investigated thoroughly the mechanisms active in laser forming. In more recent times the technique has been advanced through the development of a number of numerical [12–15], analytical [16] and finite element method (FEM) [17–21] mathematical models for various aspects of the laser forming process. Additionally, Hennige *et al.* [22], Hennige [23] and Magee *et al.* [24] have conducted studies to improve the dimensional accuracy of parts produced using laser forming, while similarly, both Sprenger *et al.* [25] and Li and Yao [26] studied the effects of stress and strain on the quality of laser bends. Both Arnet and Vollersten [27] and Vollersten *et al.* [28] have successfully demonstrated the technique's ability to form complex shapes.

In all the above studies, however, the sheet metal forming was conducted using the well-established CO<sub>2</sub> or Nd:YAG (neodymium-doped yttrium aluminium garnet) lasers. To date, only Lopez *et al.* [29] and Lawrence *et al.* [30] have investigated the possibility of forming metal sheets with the HPDL. This present work examines the effectiveness of the HPDL to carry out the laser forming of common engineering mild steel (EN3) in comparison with a CO<sub>2</sub> laser. It is believed that a number of process advantages can be realized through the employment of the HPDL as opposed to the CO<sub>2</sub> or Nd:YAG laser. These include the on-site deployment potential as a result of the HPDL's inherent portability and robustness and the better material coupling efficiency (beam absorption) of the HPDL. To date, much work has been carried out to study the effects of laser wavelength variation for medical and surgical applications, revealing clear differences in the performance and effectiveness of many different lasers for such applications. In contrast, comparisons of the differences in the beam interaction characteristics with various materials of the predominant materials processing lasers, the CO<sub>2</sub>, the Nd:YAG and the excimer lasers, are limited, with only the main fundamental differences resulting from wavelength variations being presented [31–34]. In comprehensive investigations, Lawrence and Li compared the effects of CO<sub>2</sub>, Nd:YAG, excimer and HPDL radiation on the wettability characteristics of an Al<sub>2</sub>O<sub>3</sub>/SiO<sub>2</sub> based ceramic [35], a mild steel

[36, 37] and selected biomedical polymer (PMMA) [38], noting that changes in the wettability characteristics of the ceramic and the steel varied depending upon the laser type. In addition, Lawrence and Li carried out a comparative study of the characteristic of the glazes generated on the surface of concrete with the CO<sub>2</sub> laser and the HPDL [39, 40], as well as determining the absorption depths of CO<sub>2</sub> and HPDL beams in ordinary Portland cement [41, 42] and an Al<sub>2</sub>O<sub>3</sub>-based refractory [43].

## 2 BASIC PRINCIPLES BEHIND THE LASER FORMING PROCESS

The process of laser forming is effected by introducing thermal stresses into the surface of a workpiece. These internal stresses induce plastic strains which result in the local elastic buckling of the workpiece. Essentially there are three laser forming mechanisms [10, 11]: the temperature gradient mechanism, the buckling mechanism and the upsetting mechanism. The conditions for the temperature gradient mechanism are energy parameters that led to a steep temperature gradient across the sheet metal thickness. The beam diameter is typically in the order of the sheet metal thickness, while the traverse rate has to be large enough for a steep temperature gradient to be maintained. The path of the laser beam on the surface of the metal is usually a straight line across the whole width, with this straight line being the bending edge. Initially the surface of the metal is heated, which in turn leads to pure elastic strains. Because of the thermal expansion of the surface layer of the metal there is a counter-bending of the workpiece away from the laser beam. The amount of counter-bending is very small as only the heated area on the surface, which is approximately the size of the beam spot, has to generate forces that produce the counter-bending of the whole sheet. Further heating leads to a decrease of the flow stress in the heated area and a further increase of the thermal expansion of the surface layer. At a certain temperature, which is dependent upon the material, the geometry and the degree of counter-bending, the thermal strains reach the maximum elastic strain that the metal can endure at the given temperature. A further increase in the temperature results in a conversion of the thermal expansion into plastic compressive strains. These plastic compressive strains accumulate until the laser beam moves on, allowing cooling to begin. Cooling is mainly due to self-quenching, with the heat flowing into the surrounding bulk material, resulting in cooling of the heated area within 10–20 s. During cooling shrinkage of the heated material occurs. This causes a counter-bending action on account of the fact that the surface layer was plastically compressed during heating and is therefore shorter after cooling than the non-heated layers. Because of the different lengths of the surface layer and the lower layers of the material, a bending angle develops towards

the laser beam. Typically angles of between  $0.1^\circ$  and  $3^\circ$  are achieved after one laser pass.

The buckling mechanism will occur if the laser beam diameter is large compared to the sheet metal thickness and the processing time is slow, resulting in a small temperature gradient across the sheet metal thickness. Primarily the material is heated, which in turn leads to the thermal expansion of the material and results in compressive stresses in the heated region. If the heated area is large enough and if there is a small natural deviation from the perfect plane, which normally exists in real metal sheets, an instability, or buckle, develops. In the centre of the buckle the temperature is extremely high; therefore the flow stress in this region is relatively low and the bending of the sheet in this region is consequently nearly totally plastic. In contrast, the root of the buckle, which is far away from the centre of the laser beam, is heated to a much lesser extent. Thus the temperature is low and the flow stress in this region is relatively high, resulting in completely elastic bending of the sheet in this region. By controlling certain parameters, positive (concave bending towards the laser beam) or negative (convex bending away from the laser beam) bending can be achieved with the buckling mechanism [27, 28]. As the beam is traversed along the surface the buckle shifts along the bending edge. The direction of the buckling is predetermined by the existing buckle, and as such the remaining part of the sheet buckles in the same direction. The traversing of the beam across the surface also causes the stiffness of the workpiece to alter. At the start of the buckling process the bending legs are held in the original plane due to the stiff surrounding material. As an increasing amount of the sheet is formed by the buckle, the forces that held the bending legs straight decrease. Therefore the elastic part of the buckle relaxes and only the plastic part remains in the sheet, resulting in an angular bend. Because the buckling mechanism results in more energy being coupled into the workpiece, bending angles are often up to  $15^\circ$  after one pass of the beam.

The upsetting mechanism will occur if the laser beam diameter is in the order of, or less than, the sheet metal thickness and the traverse speed is slow compared to the thermal conductivity of the material. Also, the geometry of the workpiece must be such that buckling of the material is prevented. The slow processing speed will result in almost homogeneous heating across the thickness of the sheet metal. Owing to the temperature increase, the flow stress decreases in the heated area and the thermal strains approach the elastic strains at the yield stress. Additional heating leads to a plastic compression of the heated material as it is hindered in free expansion by the surrounding bulk material. Hence a large amount of the thermal expansion is converted into plastic compression. During cooling the material contracts and the plastic compressive strain remains in the sheet for exactly the same reason as in

the temperature gradient mechanism. On account of the constancy of volume there is an increase in the sheet thickness in the compressed area.

### 3 EXPERIMENTAL PROCEDURES

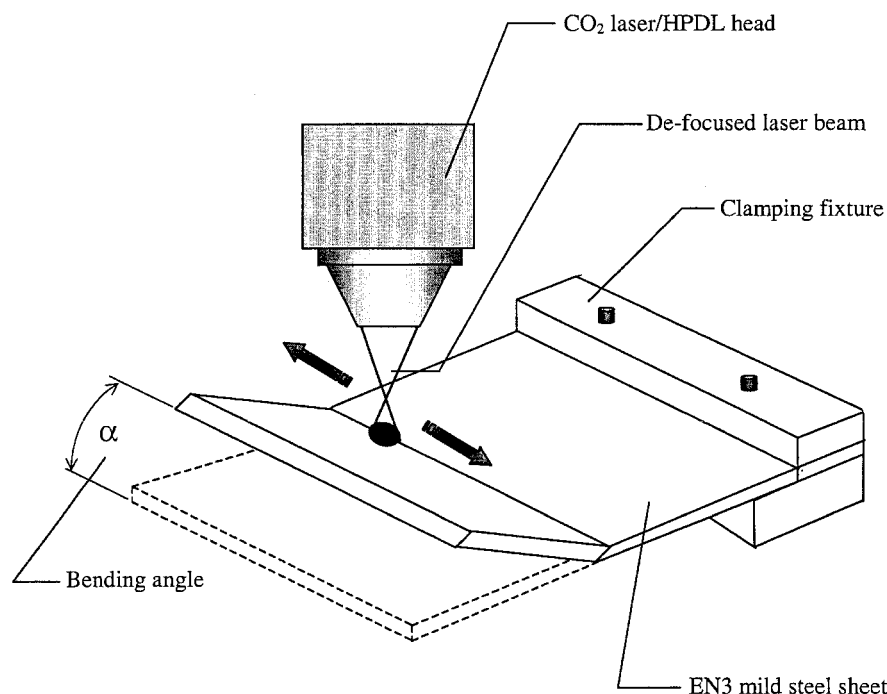
The steel used in the laser forming experiments was the ubiquitous EN3 low carbon mild steel. The mild steel was received in the form of rectangular billets ( $100 \times 50 \times 0.4 \text{ mm}^3$ ). Apart from the necessary cleaning of the billet surfaces with methanol to remove any unwanted grease, the billets were used as-received in the experiments.

The lasers used to conduct the forming experiments were a CO<sub>2</sub> laser (Rofin-Sinar) emitting a circular beam at  $10.6 \mu\text{m}$  with a maximum output power of 1 kW and an HPDL (Rofin-Sinar) emitting a rectangular beam at 940 nm with a maximum output power of 1.2 kW. The CO<sub>2</sub> laser beam was delivered to the work surface by focusing the beam through a 150 mm focal length KCl lens to give a stable converging beam. The HPDL beam was focused directly on to the workpiece. Both lasers produced a multimode beam. In order to obtain a reasonably direct comparison of the effectiveness of both lasers for the forming of the EN3 mild steel sheets, the laser power densities used were set to approximately the same value by manipulating the spot sizes of the beams such that the incident areas were the same. Thus for the CO<sub>2</sub> laser the beam spot size was 4.5 mm in diameter, while the spot size of the HPDL beam was  $4 \times 4 \text{ mm}^2$ . The sizes of the beams were measured using the standard burn paper procedure. The general laser processing experimental arrangement is shown schematically in Fig. 1. Essentially the defocused laser beams were fired back and forth along the same path on the surface of the mild steel sheet by traversing the samples beneath the laser beams using the  $x$  and  $y$  axes of a computer numerical control (CNC) gantry table. The beams of both lasers impinged on the surface of the mild steel samples perpendicularly.

No surface melting of the mild steel was observed on any of the samples during or on completion of the laser forming. In all the experiments, the holding time between each irradiation was fixed at 0 s. The bending angles obtained as a result of forming with both lasers were digitally captured using a charge-coupled device (CCD) camera and measured to an accuracy of  $\pm 0.1^\circ$  using image processing software (Visilog 5).

### 4 RESULTS

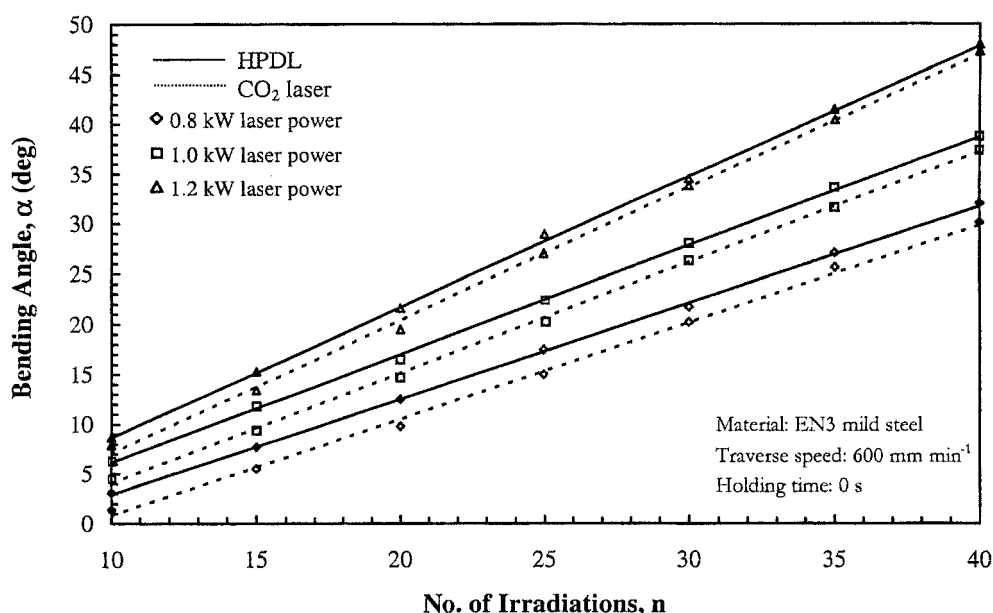
The mechanism responsible for the forming of the EN3 mild steel sheets when using both the CO<sub>2</sub> laser and the HPDL can be attributed entirely to the buckling mechanism. This assertion can be made because,



**Fig. 1** Schematic illustration of the experimental set-up for the CO<sub>2</sub> laser and the HPDL forming of EN3 mild steel sheets

according to the work of Arnet and Vollersten [27] and Vollersten *et al.* [28], if the size of the laser beam employed is large compared to the sheet metal thickness then forming of the metal sheet is effected by the buckling mechanism. This is certainly the case in this present study where the beam size for both lasers was only 16 mm<sup>2</sup> while the EN3 mild steel sheets had a thickness of 0.4 mm.

The relationship between the laser bending angle and the number of irradiations in a multiple-irradiation process is best represented by an  $\alpha$ - $n$  curve, where  $\alpha$  is the bending angle and  $n$  is the number of irradiations [44]. The  $\alpha$ - $n$  curves for the EN3 mild steel sheets obtained at different laser powers but with a fixed traverse speed of 600 mm/min are given in Fig. 2. It is evident from Fig. 2 that the bending angles obtained



**Fig. 2** The  $\alpha$ - $n$  curves obtained for the CO<sub>2</sub> laser and the HPDL at different laser powers (600 mm/min traverse speed)

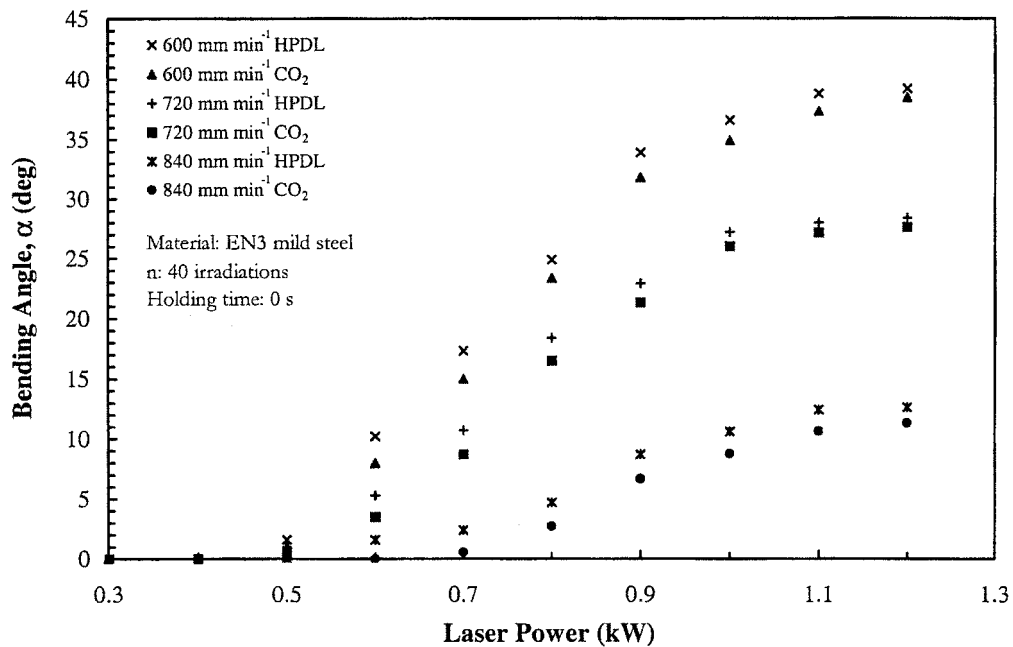


Fig. 3 Effect of laser power on the final bending angle for the CO<sub>2</sub> laser and the HPDL (after 40 irradiations)

when employing the HPDL were consistently greater than those obtained with the CO<sub>2</sub> laser. It is also apparent from Fig. 2 that for both lasers, the bending angle induced in the EN3 mild steel sheets increased almost linearly with the increasing number of irradiations, with the degree of linearity being greatest for the HPDL. At the same time, the gradients of the curves can be seen to increase with increasing laser incident power. The effect of laser power on the final bending angle (after 40 irradiations) at different traverse speeds was investigated and the results are shown in Fig. 3. It

can be seen from Fig. 3 that a laser power threshold exists for both lasers, below which no bending will occur. Furthermore, it is clearly apparent from Fig. 3 that for both the CO<sub>2</sub> laser and the HPDL, a certain critical value of laser power exists, beyond which further increases in power, regardless of the magnitude, bring about only marginal increases in the bending angle.

Similarly, the effects of varying the traverse speed while keeping the laser power at a fixed value of 1 kW on the  $\alpha$ - $n$  curves for the EN3 mild steel sheets are shown in Fig. 4. Again, the bending angles occasioned

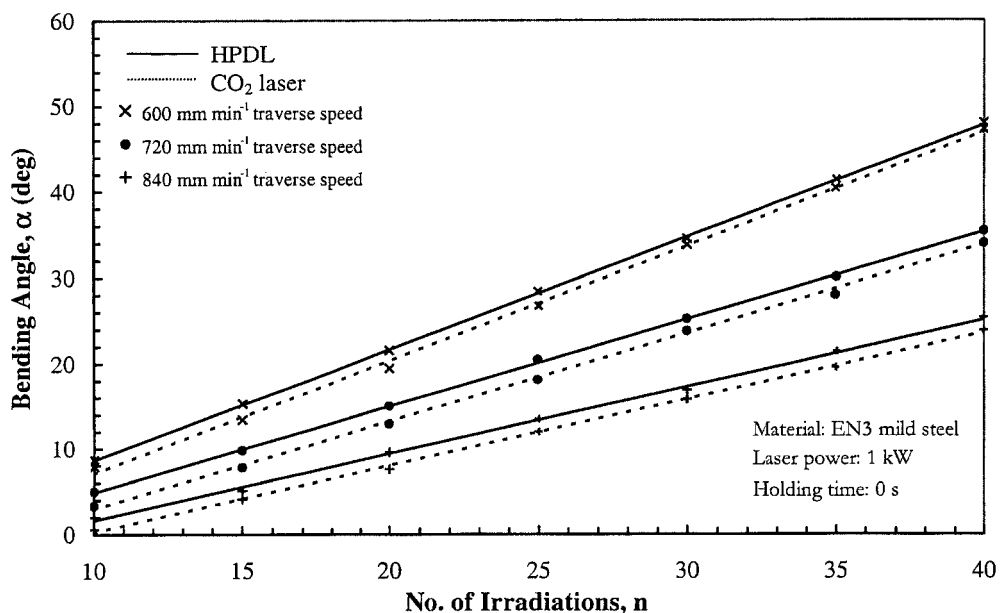


Fig. 4 The  $\alpha$ - $n$  curves obtained for the CO<sub>2</sub> laser and the HPDL at different traverse speeds (1 kW laser power)

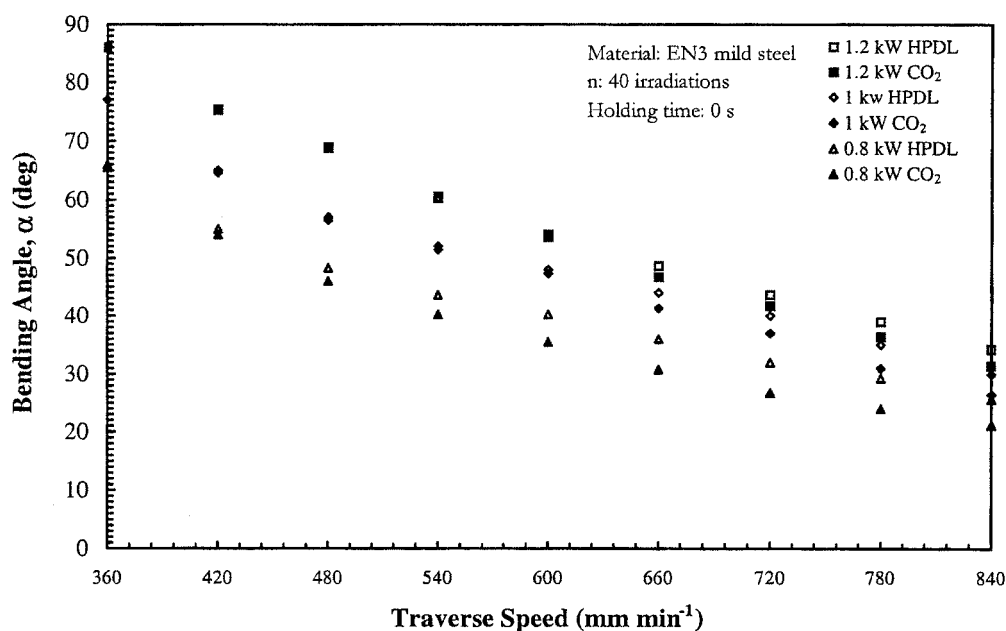


Fig. 5 Effect of traverse speed on the final bending angle CO<sub>2</sub> laser and the HPDL (after 40 irradiations)

after HPDL irradiation are consistently greater than those of the CO<sub>2</sub> laser. Also, as before, the bending angle was seen to increase almost linearly with the number of irradiations for both lasers, with the results of the HPDL exhibiting a greater degree of linearity than those of the CO<sub>2</sub> laser. Even so, the gradients of the curves for both lasers decreased as the traverse speed was increased. The influence of traverse speed on the final bending angle (after 40 irradiations) is shown in Fig. 5 and reveals that for both lasers the induced bending decreased in gradual increments as the traverse speed increased. In addition, Fig. 5 shows that at the lower traverse speeds (less than 540 mm/min) the curves for the CO<sub>2</sub> laser and the HPDL were more comparable than at higher traverse speeds, especially at the highest laser powers. Still further, as the traverse speed increases then the accord between the curves of the two lasers diminishes.

## 5 DISCUSSION

The observance of a linear relationship between the laser bending angle and the number of irradiations seen on the  $\alpha$ - $n$  curves, particularly for the HPDL, in Figs 2 and 4 is in general agreement with the findings of a number of workers [6, 44, 45]. However, such findings are at odds with those of other researchers [24, 25] who have reported a decaying increase in the bending angle with an increasing number of irradiations. This significant difference between the findings of this study and those of the latter workers is believed to be due to different degrees of local thickening and strain hardening of the EN3 mild steel sheet during HPDL bending. From

comprehensive studies conducted by Vollersten [7] and Sprenger *et al.* [25], the laser bending angle was said not to increase linearly with the number of irradiations due to: (a) changes in the absorption behaviour of the steel with increasing irradiations, (b) the increase in the sheet thickness along the bending edge and (c) the strain hardening effect on the underside of the sheet.

By virtue of its beam wavelength, the HPDL enjoys relatively high levels of beam absorption with many metallic materials, as confirmed by Fig. 6. For mild steel the absorption of HPDL radiation is around 45 per cent compared with only 15 per cent for the CO<sub>2</sub> laser [29]. With such a considerable difference in beam absorption between the CO<sub>2</sub> laser and the HPDL, it is reasonable to cite beam absorption, and ultimately laser wavelength, as one of the major influences on the differences in the performance of the CO<sub>2</sub> laser and the HPDL for the laser forming process. This postulation is borne out somewhat when consideration is given to the convergence to varying degrees in forming performance of the CO<sub>2</sub> laser and HPDL observed when the laser power was increased (Figs 2 and 3) and when the traverse speed was decreased (Figs 4 and 5). Both of these actions, increasing the laser power incident on a surface and reducing the traverse speed of an incident laser beam across a surface, are tantamount to much the same thing, namely increasing the energy deposited on the surface itself. The outcome of this increase in the amount of energy deposited on a surface, in this case the surface being that of the EN3 mild steel sheets, is that the temperature of the surface, particularly in the region of laser interaction, will increase. This induced increase in temperature, in turn, affects the absorption characteristics of the metal. According to von Allmen

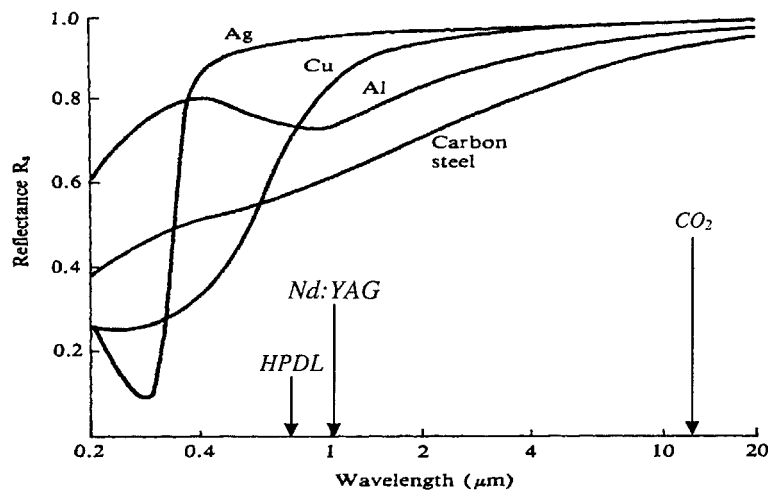


Fig. 6 Reflectance versus wavelength of various polished metal surfaces [46]

and Blatter [44], the bulk absorption of metals increases with temperature due to the apparent electron–lattice collision time shortening. In addition, hot metals are reactive and irreversible changes in reflectance resulting from chemical reactions at the surface (e.g. oxidation) tend to take place. This being the case, then, as the energy deposited on the surface of the EN3 mild steel sheets increased as a result of either an increase in the laser power or a decrease in the traverse speed, the subsequent increase in the surface temperature will lead to an increase in the beam absorption and thus an increase in the induced bending angle. However, the results in Figs 2, 3, 4 and 5 show the performance of the CO<sub>2</sub> laser in terms of induced bending angle to be approaching that of the HPDL under these conditions, implying that an increase in laser beam absorption is only occasioned for the CO<sub>2</sub> laser. Indeed, this may be so, as minimized changes in absorptivity have been observed previously by Scully [45] for the Nd:YAG laser. Since the wavelength of the HPDL is very similar to that of the Nd:YAG laser, 940 and 1064 nm respectively, then it is reasonable to assume that such minimized changes in the absorptivity will occur likewise with the HPDL. As such, it appears that under the conditions of either increased laser power or decreased traverse speed, the effectiveness of the CO<sub>2</sub> laser for forming is similar to that of the HPDL in that similar bending angles are induced in the EN3 mild steel sheets. However, as can be seen from Figs 2 and 4, convergence in performance is dependent on temperature effected reductions in reflectance and similar results between the two lasers are only achieved with increasing irradiations. It is therefore reasonable to assert that, overall, the bending effectiveness of the HPDL is greater than that of the CO<sub>2</sub> laser insofar as it is more efficient, since the difference in the beam absorption of the two lasers is so much greater than the difference in the actual forming performance. Additionally, it is worth noting that a factor that is

likely to have been influential is that of beam geometry. Naturally, differences in the beam absorption and the heat diffusion within the EN3 mild steel sheets will have occurred on account of the fact that a circular beam was produced by the CO<sub>2</sub> laser while the HPDL beam was rectangular in shape.

It is known that strain hardening only comes into play during laser bending for relatively thick sheets of typically more than 1 mm in thickness [24]. Moreover, if the sheet is relatively thin, as was the case in this study, the influence of strain hardening and material thickening along the bend edge can be considered to be almost insignificant when the number of irradiations is small [47]. Hence a linear relationship between the bending angle and the number of irradiations will exist. Nevertheless, strain hardening and material thickening along the bend edge is unavoidable if the number of irradiations increases. This is principally because local thickening will occur under the temperature gradient mechanism, causing the sheet to increase its thickness locally in the irradiated (and thus heated) zone. In addition, the bending angle enlarges when the number of irradiations increases; therefore more work has to be done on the underside of the sheet, which subsequently leads to strain hardening on the underside of the sheet. It is thought, therefore, that the bending angle will no longer be linearly proportional to the number of irradiations as the effects of strain hardening and material thickening along the bend edge become more pronounced. This supposition is confirmed somewhat by Fig. 7. Here the number of irradiations was increased considerably from the experimental normal of 40–80 irradiations for both lasers. It is possible to discern from Fig. 7 that for both the CO<sub>2</sub> laser and the HPDL, the increase in the bending angle is no longer linearly proportional to the number of irradiations when the latter exceeds around 60 irradiations. It is therefore possible to conclude that for the CO<sub>2</sub> laser and HPDL bending of the EN3 mild steel sheets used in this present study,

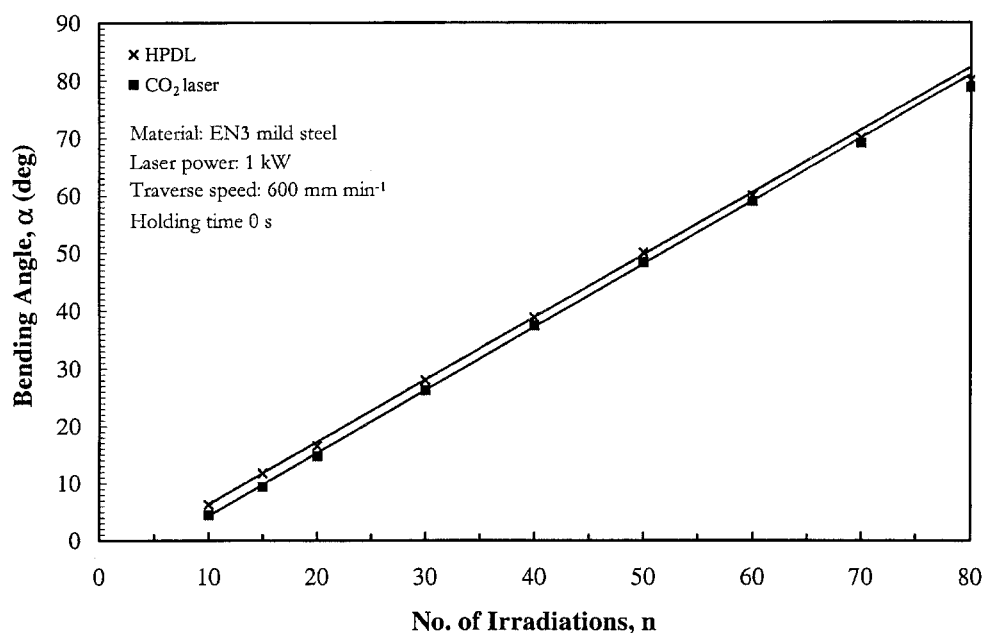


Fig. 7 The  $\alpha$ - $n$  curve obtained for a large number of irradiations for the CO<sub>2</sub> laser and the HPDL

the bending angle is only linearly proportional to the number of irradiations when the latter is small, less than approximately 60 irradiations but greater than 10 irradiations.

As can be seen from Fig. 3, a laser power threshold for both lasers exists below which no bending could be occasioned. Such a finding concurs with that of Holt [4], who noted that a critical temperature was required for thermal upsetting or a permanent change in shape to take place. It is also apparent from Fig. 3 that as the laser power was increased beyond a certain value,

which differed depending upon the laser and traverse speed used, the induced increases in the bending angle were only marginal. This is believed to be due to the fact that at high laser power, the resultant heat generated will penetrate fully to the underside of the sheet. To determine the significance of these observed thresholds further, it was necessary to examine the relationship between the laser bending angle and the laser line energy (with the laser line energy being defined by the ratio of the laser power and the traverse speed). This relationship is shown in Fig. 8, from which it is apparent

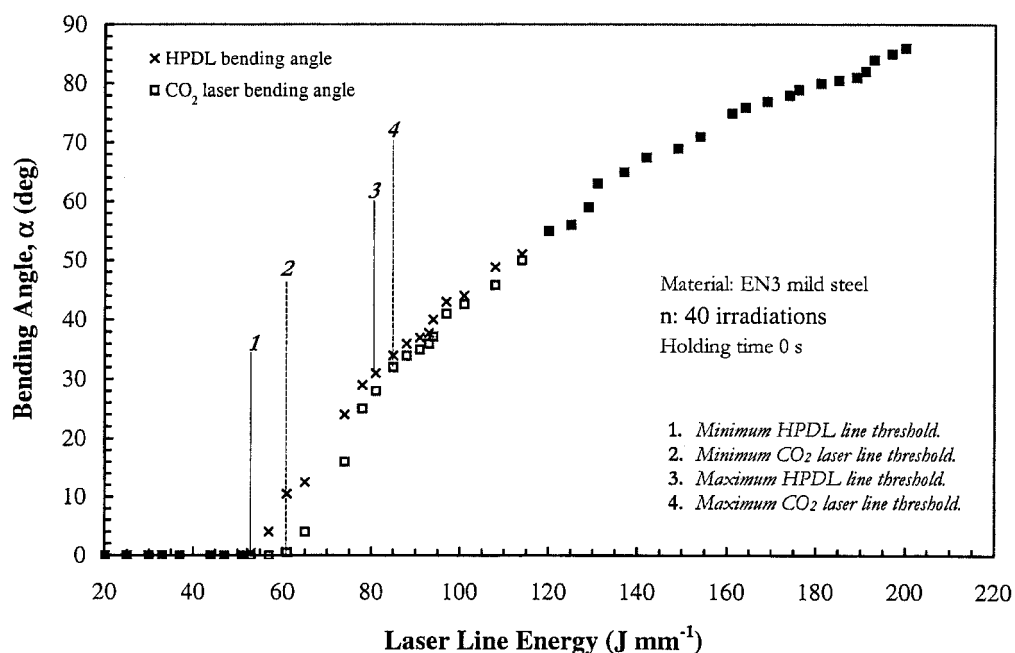


Fig. 8 Relationship between the bending angle and the laser line energy for the CO<sub>2</sub> laser and the HPDL



that a threshold energy input of around 53 and 61 J/mm exists for the HPDL and the CO<sub>2</sub> laser respectively. Also, an almost linear region can be seen below 78 and 85 J/mm for the HPDL and the CO<sub>2</sub> lasers respectively. These limits to the linearity of the process represent the maximum laser line thresholds; i.e. they are the values of laser line energy at which the bend angle is linearly related to the laser line energy and are therefore the points beyond which further increases in the laser line energy result in less overall controllability of the bend angle, and in turn the process as a whole. More specifically, the threshold values indicate the range in which the bending process can be operated most effectively and efficiently. The fact that a smaller amount of laser line energy is required to initiate bending with the HPDL is further confirmation that the HPDL is more efficient for the laser bending process than the CO<sub>2</sub> laser.

Such linearity, coupled with the existence of a minimum laser line energy threshold, indicates that the induced bending angle could be accurately controlled for both lasers by adjusting the laser operating parameters. Furthermore, the presence of this linearity and the minimum laser line energy threshold conforms with the analytical model developed by Yau *et al.* [48]. According to this model, the laser bending angle can be expressed by

$$\alpha = \frac{3\beta AP}{\rho C_p v h^2} \left( \frac{7}{2} \right) - 36 \frac{l}{h} \frac{Y}{E} \quad (1)$$

with the critical condition for bending to occur being given by

$$\frac{AP}{vl} \geq \frac{12(1+m^2)}{7(1+m)} \frac{Y\rho C_p}{E\beta} h \quad (2)$$

where  $\alpha$  is the final laser bending angle,  $\beta$  is the coefficient of thermal expansion,  $A$  is the absorptivity,  $\rho$  is the density,  $C_p$  is the heat capacity,  $Y$  is the yield strength,  $E$  is Young's modulus,  $h$  is the thickness,  $m$  is the thickness ratio,  $P$  is the laser power,  $v$  is the traverse speed and  $l$  is the beam radius. However, since only one type of material is under investigation, equation (2) can be simplified to

$$\frac{P}{v} \geq C' \quad (3)$$

where  $C'$  is a constant relating to both the material and the geometry characteristics of the EN3 mild steel sheets. Thus, from equation (3) it can be deduced that to exercise accurate control of the HPDL bending of the EN3 mild steel sheets investigated, it is necessary that the process should be operated in the range of 53 J/mm <  $P/v$  < 78 J/mm. Likewise for the CO<sub>2</sub> laser, accurate control of the process can be obtained from operating within 61 J/mm <  $P/v$  < 85 J/mm. The fact that a smaller amount of laser line energy is required to

initiate bending with the HPDL is further confirmation that the HPDL is more efficient for the laser bending process than the CO<sub>2</sub> laser.

## 6 CONCLUSIONS

A comparative investigation of the forming of EN3 mild steel sheet (100 × 50 × 0.4 mm<sup>3</sup>) to various degrees using a contemporary 1.2 kW high-power diode laser (HPDL) and a 1 kW CO<sub>2</sub> laser has been conducted. Because the size of the beams of both lasers employed in this study were large (16 mm<sup>2</sup>) compared to the sheet metal thickness (0.4 mm), the buckling mechanism was identified as the laser forming mechanism responsible for the induced bending. For both lasers it was found that the induced bending angles increased with an increasing number of irradiations and high laser powers, while decreasing as the traverse speed was increased. Also, it was apparent from the experimental results that the laser bending angle was only linearly proportional to the number of irradiations when the latter was small, less than approximately 60 irradiations and greater than 10 irradiations. It is believed that the absence of linearity observed when more than around 60 irradiations were used is due to local material thickening along the bend edge. Owing to its greater beam absorption by the EN3 mild steel (45 per cent for the HPDL compared with only 15 per cent for the CO<sub>2</sub> laser), larger bending angles were induced when using the HPDL. However, increases in the energy deposited on the surface of the EN3 mild steel sheets, as a result of either an increase in the laser power or a decrease in the traverse speed, subsequently increased the surface temperature and led to an increase in the beam absorption and thus an increase in the induced bending angle. However, due to only minimized changes in the absorptivity of the EN3 mild steel at the HPDL wavelength, the performance of the CO<sub>2</sub> laser in terms of induced bending angle was seen to approach that of the HPDL under these conditions. Nevertheless, similar results between the two lasers were only achieved with increasing irradiations and it is therefore reasonable to assert that, on the whole, the performance of the HPDL is more effective than that of the CO<sub>2</sub> laser insofar as it is more efficient. From graphical results and the employment of an analytical procedure, the laser line energy range in which accurate control of the HPDL bending of the EN3 mild steel sheets could be exercised was found to be 53 J/mm <  $P/v$  < 78 J/mm, while for the CO<sub>2</sub> laser the range was 61 J/mm <  $P/v$  < 85 J/mm.

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